URN (Paper): urn:nbn:de:gbv:ilm1-2014iwk-001:6

58th ILMENAU SCIENTIFIC COLLOQUIUM
Technische Universität Ilmenau, 08 – 12 September 2014
URN: urn:nbn:de:gbv:ilm1-2014iwk:3

COMPLEXITY OF MECHATRONIC SYSTEMS ON EXAMPLE OF MOBILE ROBOTS

F. Schale, M. Braunschweig, S. Frank
Technische Universität Ilmenau

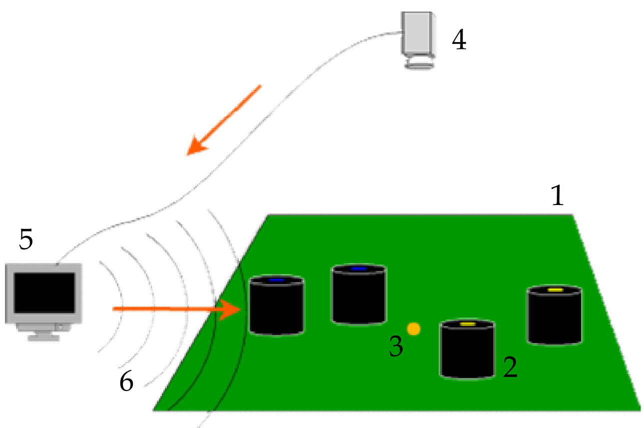
ABSTRACT

Mobile robots do not only get a greater importance in industrial applications but also in the private sector. In the near future assistance and care robots will also arrive at everyday life. In addition to their actual tasks the mobility of the robots is always the basic requirement. To meet this requirement of mobile robots a great variety of basic tasks has to be solved, e.g.:

> electrical power supply, energy control, orientation and navigation, obstacle detection, position- and drive control, communication between subsystems and with the environment

These tasks are typical for mechatronic systems (mechanics, electronics and computer science).

This paper is supposed to represent the complexity and the resulting subtasks of mobile robot systems. For the example of the RoboCup Small Size League (**Fig 1**) a new solution to the soccer robot M11 (**Fig 2**) is presented and the achieved results are represented. In the Small Size League five robots per team play soccer with an orange golf ball on a 6.05 m x 4.05 m large playing field, over which there is a camera for players detection [SSL01].



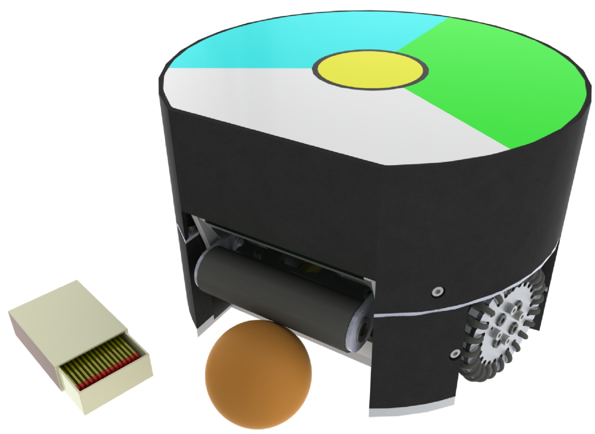


Fig 1: RoboCup Small Size League system overview [RBC01], (1) playing field, (2) robot, (3) golf ball, (4) camera, (5) host PC, (6) wireless connection

Fig 2: mobile robot system M11 in size comparison with a matchbox, robot Ø 180mm x 120mm, ball Ø 46mm

1. INTRODUCTION

"RoboCup is an international scientific initiative with the goal to advance the state of the art of intelligent robots"[RBC02]. The original idea was to create a robot soccer team that would be able to win against a human team by 2050 [RBC02]. Meanwhile, there are many different categories follow different approaches on mobile robotics. The presented football robots belong to the category of Small Size League RoboCup Soccer.

The design of the robot M11 (**Fig 2**) is based on the regulations of the RoboCup Small Size League [SSL02], so that in addition to the dimensions (Ø 180mm x 120mm) and the running time (about 30 minutes), the typical football tasks (pass, shot, ...) must be realized by the robot. The system of the Small Size League provides external obstacle detection by an image processing software as well as the planning of the intelligent football game, so that the robot does not need high-performance computing and sensor technology for these tasks.

A personal computer captures video frames from a camera, searches for the location of the soccer robots and the ball on the playing field and calculates the following instructions (drive to, pass, shot, etc.) which are transmitted by a wireless connection to the robots (**Fig 1**). The complete system works without human interventions and so it can be considered as autonomous system.

2. CHARACTERISTICS OF MECHATRONIC SYSTEMS

First of all let's take a look on a basic structure of each mechatronic system (**Fig 3**). This concept is presented in the guideline VDI2206: "Design methodology for mechatronic systems" and can be adapted for all mechatronic systems. The scheme shows the interaction (flow of information, energy and material) between specific classes of subsystems and between these subsystems and the world around. The centerpiece based on the classic control loop of control engineering, which is necessary to realize the requested tasks of the mechatronic system.

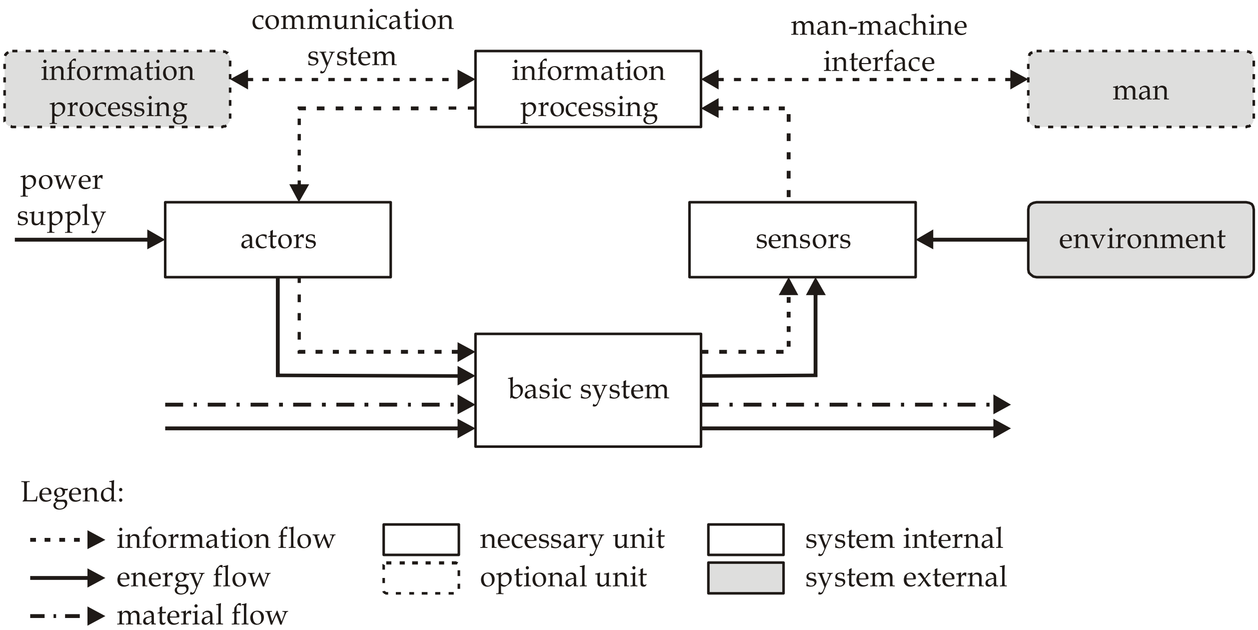


Fig 3: Basic structure of a mechatronic system [VDI2206]

The main idea of this flowchart is to illustrate the complex structures and the interaction of the mechatronic system to an abstract form, so that the overview is never lost during the development.

3. MECHATRONIC SYSTEM SOCCER ROBOT M11

Because tasks such as path planning and obstacle detection in the RoboCup Small Size League are realized by an external system, the two main tasks for soccer robots are:

Task	Requirements
move to position x, y, φ	position controller, position measurement system
manipulate the ball	shot mechanism, dribbler

Implementing several other tasks is helpful to increase the efficiency, the runtime and the longevity of the robot. Therefore a battery monitoring system (to supervise the two battery packs), a wireless communication module (to communicate with the host PC and other robots) and also an internal communication bus (for data exchange between subsystems, sensors, etc. and expandability of the robot system) are also part of the robot M11.

The robot has a special design with three Omni directional, direct driven wheels (**Fig 4**, **Fig 5**). The construction of these wheels makes it possible that the wheels can rolls sideward. So it is also possible that the robot can make a translation in each direction (x, y) in combination with simultaneously rotation around the normal axis (φ).

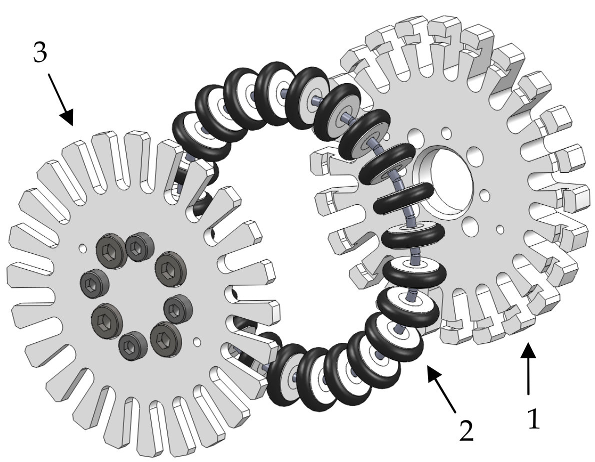


Fig 4: exploded perspective view of a Omni directional wheel
(1) inner rim , (2) 24 sub wheels, (3) outer rim

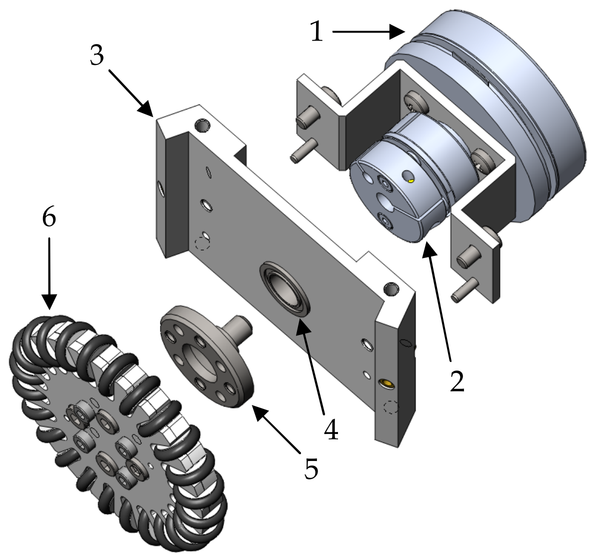


Fig 5: exploded perspective view of one drive
(1) BLDC motor, (2) coupling, (3) robot housing, (4) bearing, (5) wheel shaft, (6) Omni directional wheel

The three motors[1] are Brushless DC (BLDC) motors[2] with integrated hall sensors. The arrangement of the three drives in the robot is shown in **Fig 6** and described in the local robot coordinate system $\vec{E}_x$, $\vec{E}_y$, $\vec{E}_\varphi$. The robot position itself is described in the global coordinate system $\vec{e}_x$, $\vec{e}_y$ by the vector $\vec{r}$ and the angle φ between $\vec{e}_x$ and $\vec{E}_x$.

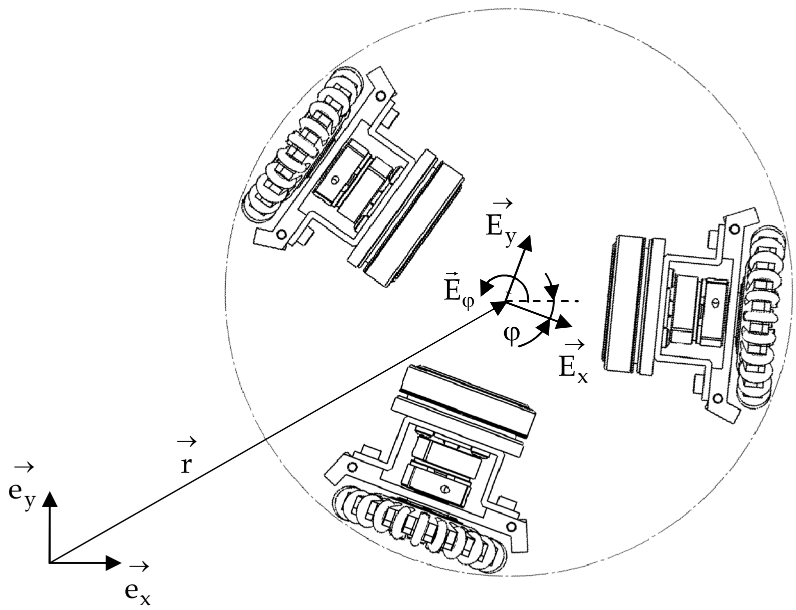


Fig 6: Schematic representation of the arrangement of drives in the robot[3]

For the mechatronic model all non moving parts (e.g. housing, covering, battery packs, electronic circuit boards, sensors, etc.) of the robot are combined to a rigid mechanical system.

The autonomous power supply is done by two battery packs, consisting of seven LiFePo4 battery cells[4] in each pack[5]. The nominal supply voltage is about 23.1 V with a maximum of 2200mAh of energy. Furthermore, there is a small Lithium Ion battery cell as backup battery for the logic supply of the battery monitoring system and wireless communication.

For wireless data exchange with the host PC and other robots a XBee S1[6] module is used in API configuration for direct addressable devices. The manipulation of the ball is done with help of a spring shot mechanism with adjustable shot speeds and a rotating dribbler roll to pull the ball back while the robot moving backwards. Detailed technical information about the shot mechanism and wireless data transfer are not part of this paper.

---

[1] used motors are Maxon Ec45-flat Brushless DC motor

[2] "Brushless DC electric motor (BLDC motors, BL motors) also known as electronically commutated motors (ECMs, EC motors) are synchronous motors that are powered by a DC electric source via an integrated inverter/switching power supply, which produces an AC electric signal to drive the motor." [WIK01]

[3] the illustrated circle corresponds to the maximal design space, which is determined by the regulations of the RoboCup Small Size League

[4] the seven LifePo4 cells are connected in series, each cell has a nominal voltage of 3.3V and a nominal capacity of 1100mAh

[5] the two batterypacks are connected in parallel mode to increase the capacity and reducing the current load for the single battery pack

[6] XBee is a low power 2.4GHz RF module by the company Digi.

Thus a concretization of the basic structure of mechatronic systems (**Fig 3**) to a specific overview of the robot M11 (**Fig 7**) is possible.

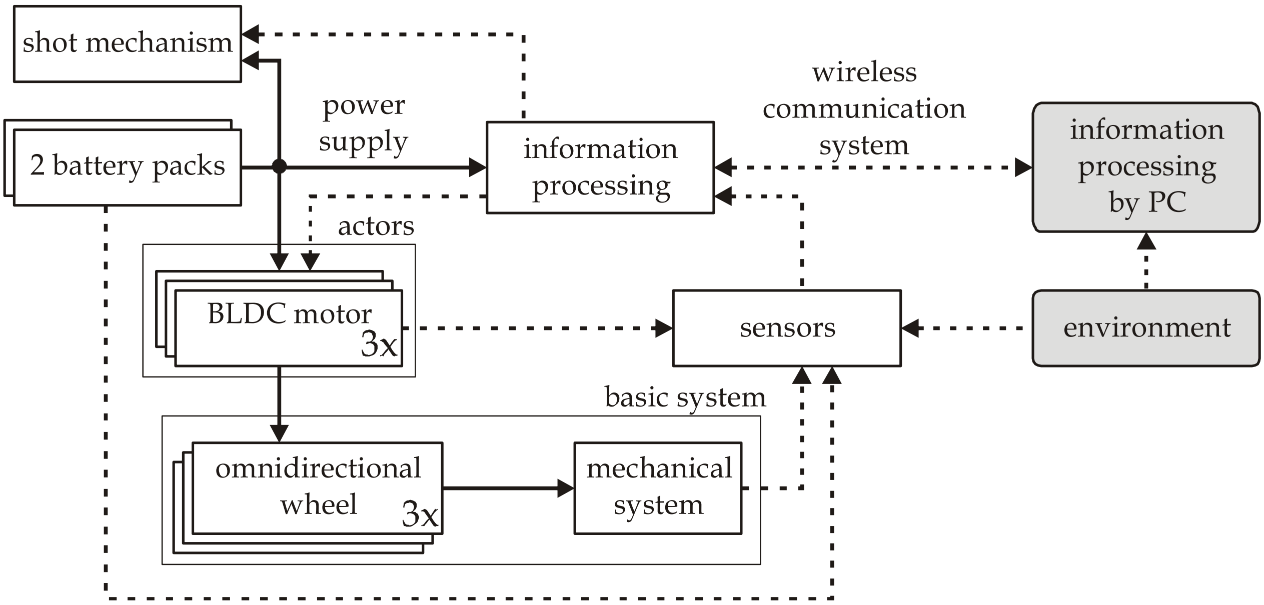


Fig 7: Overview of the robot M11

4. POSITION CONTROLLER

The position controller concept (**Fig 8** [USS13]) based on the idea that each drive generates a specific drive force and the sum of these forces accelerates the robot with the limitations of wheel traction and motor power. To move as fast as possible the maximal transferable acceleration, without slipping wheels, is calculated with help of a mechatronic robot model.

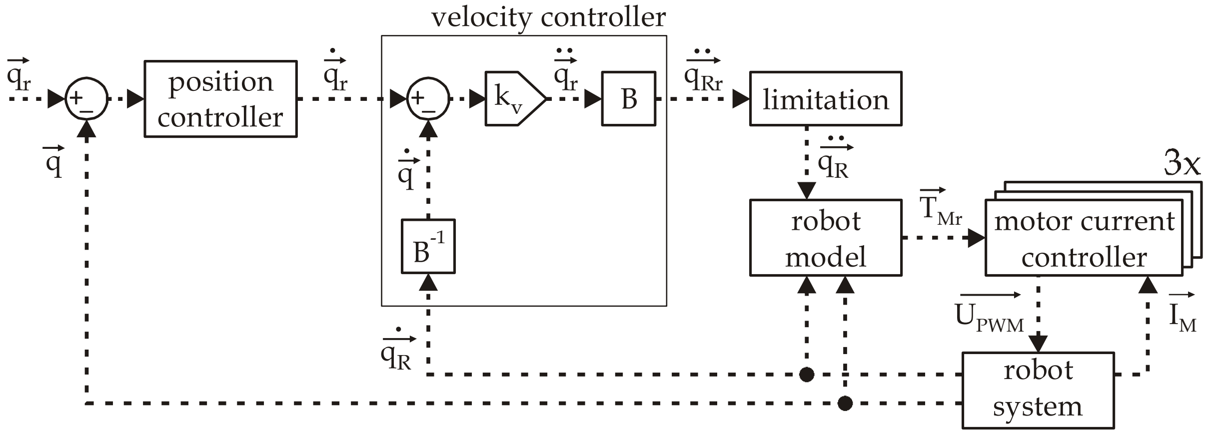


Fig 8: Position controller concept

The vector $\vec{q}$ represents the robot position, $\vec{q}_r$ represents the requested target position value.

$$\vec{q} = \begin{pmatrix} x \cdot \vec{e}_x \\ y \cdot \vec{e}_y \\ \varphi \cdot \vec{E}_\varphi \end{pmatrix} \qquad (\,I\,)$$

All values with index R are transformed values from the global coordinate system in the local robot coordinate system.

The transformation between these coordinate systems is done by the rotation matrix B and the robot orientation angle φ.

$$B = \begin{pmatrix} \cos(\varphi) & \sin(\varphi) & 0 \\ -\sin(\varphi) & \cos(\varphi) & 0 \\ 0 & 0 & 1 \end{pmatrix} \qquad (\text{II})$$

With the information the maximal reachable acceleration a cascaded position and velocity controller generates, depending on the robot state[7] and the restrictions of the mechatronic model, three requested motor torques $\vec{T}_{Mr}$. Thus, it is necessary to control the motor torques by controlling the motor currents $\vec{I}_M$, which are measured with two Hall Effect current sensors[8] for each motor[9]. Combined with the hall sensor information the BLDC motor is commutated and the torque is controlled[10] [SCH10] by a Field Orientated Control. At least a PWM[11] driven 3-phase motor inverter is used to actuate the motor (**Fig 9**).

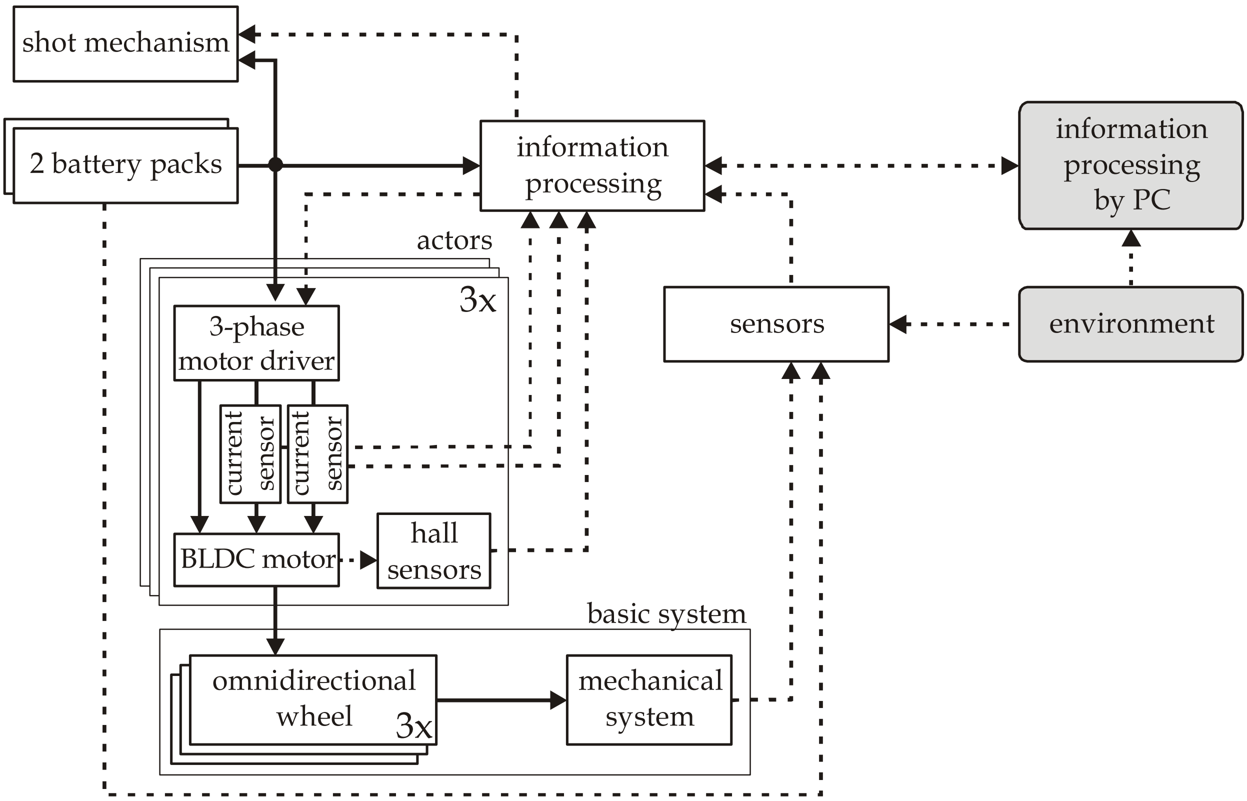


Fig 9: Detailed structure of the mechatronic robot system M11 - motor controlling

---

7 Robot position $\vec{q}$, robot velocity $\dot{\vec{q}}$, motor state and battery charging level

8 The used sensors are Allegro ACS711 integrated circuits with extra operation amplifiers to increase the current measurement sensivity up to 500mV/A

9 BLDC motors are 3-phase motors with a wye winding style. To know all the phase currents, two of these has to be measured, the third one is the sum of the two others (Kirchhoff's circuit laws).

10 There are three basic concepts to commutate and control BLDC motors: Trapezoidal Commutation, Sinusoidal Commutation and Field Oriented Control [SCH10]

11 Pulse-width modulation

5. POSITION SENSOR SYSTEM

To realize the position controller information about the robot position is absolutely essential. The in [FUS11] and [DIL11] presented concept of a laser measurement system is implemented in the robot structure. This system is characterized by the arrangement of three optical laser sensors[12] (**Fig 10**) at the bottom of the robot looking down on the floor. Each sensor includes a light emitter, an optical lens and a picture sensor to detect the movement of the sensor (**Fig 12**). The numeric sensor output data provides information about the relative movement of the sensor in its own coordinate system $\vec{e}_{sx}$, $\vec{e}_{sy}$.

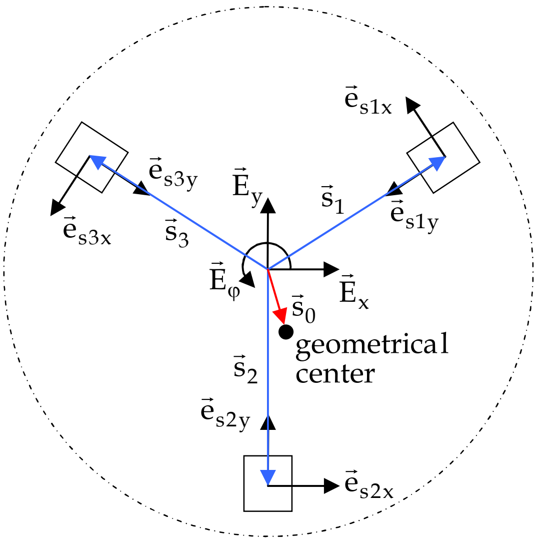


Fig 10: Arrangement of optical three laser sensors ($\vec{s}_1, \vec{s}_2, \vec{s}_3$) in the robot with sensor coordinate systems

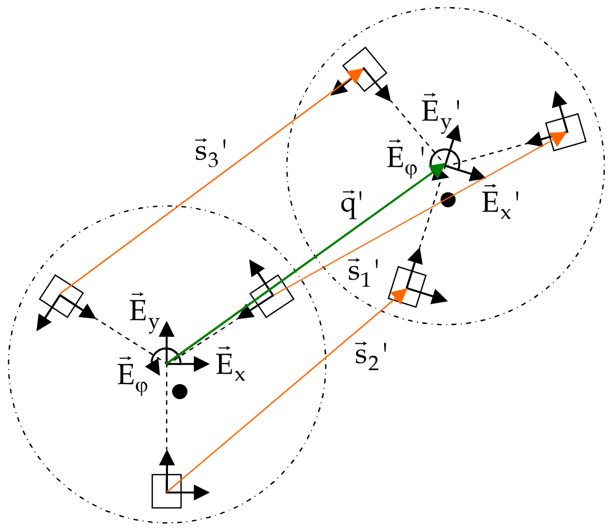


Fig 11: Differential small robot movement ($\vec{q}\,'$) between two measurements and sensor information ($\vec{s}_i\,'$)

With the 2D Helmert transformation **(III)** it is possible to combine the information of the three sensors to a relative movement $\vec{q}\,'=(\Delta x \quad \Delta y \quad \Delta\varphi)^T$ of the robot. The sensor data $\vec{s}_i\,'$ is used to calculate the new geometrical center $\tilde{x}'$, $\tilde{y}'$ described in the origin coordinate system $\vec{E}_x$, $\vec{E}_y$.

$$m \cdot \begin{bmatrix} \cos(\Delta\varphi) & -\sin(\Delta\varphi) \\ \sin(\Delta\varphi) & \cos(\Delta\varphi) \end{bmatrix} \cdot (\vec{s}_i - \vec{s}_0) = (\vec{s}_i + \vec{s}_i\,') - \vec{s}_0\,' + \vec{\varepsilon} \qquad \text{(III)[13]}$$

$$\vec{s}_0 = \begin{pmatrix} \tilde{x} \\ \tilde{y} \end{pmatrix}, \quad \vec{s}_0\,' = \begin{pmatrix} \tilde{x}' \\ \tilde{y}' \end{pmatrix} \qquad \text{(IV)[14]}$$

$$\tilde{x} = \tfrac{1}{n}\sum_{i=1}^{n=3} \vec{s}_{ix}, \quad \tilde{y} = \tfrac{1}{n}\sum_{i=1}^{n=3} \vec{s}_{iy}, \quad \tilde{x}' = \tfrac{1}{n}\sum_{i=1}^{n=3} (\vec{s}_{ix} + \vec{s}_{ix}\,'), \quad \tilde{y}' = \tfrac{1}{n}\sum_{i=1}^{n=3} (\vec{s}_{iy} + \vec{s}_{iy}\,') \qquad \text{(V)}$$

The result of the optimization problem $\vec{\varepsilon} \to \min$ and finding the best approximation of redundant sensor information are the two transformation parameters o and a [GJ07][USS13].

---

[12] used sensor is Avago ADNS9500

[13] m is a scaling factor between the origin and the target coordinate system. $\vec{\varepsilon}$ is a approximation error.

[14] $\tilde{x}$, $\tilde{y}$ describes the geometrical center (not necessarily the center of the robot!) of the three sensors in the local coordinate system $\vec{E}_x$, $\vec{E}_y$.

$$\vec{S}_i = \vec{s}_i - \vec{s}_0 \;, \quad \vec{R}_i = (\vec{s}_i + \vec{s}_i') - \vec{s}_0' \tag{VI}$$

$$a = \sum_{i=1}^{n=3} (R_{ix} \cdot S_{ix} + R_{iy} \cdot S_{iy}) \;, \quad o = \sum_{i=1}^{n=3} (R_{iy} \cdot S_{ix} + R_{ix} \cdot S_{iy}) \tag{VII}$$

$$\Delta x = \tilde{x}' - (o \cdot \tilde{x} - a \cdot \tilde{y}), \quad \Delta y = \tilde{y}' - (a \cdot \tilde{x} + o \cdot \tilde{y}), \quad \Delta\varphi = \arctan\left(\frac{a}{o}\right) \tag{VIII}$$

The sum of all small movements since the last adjustment is the current position of the robot. After a floor material and robot specific calibration routine [SCH12] is done the position measurement results are of good quality. The following table shows measurement result of the calibrated system for translation and rotation with a quantity of retries n=30.

Pattern of movement	Translation[15] (n=30)			Rotation[16] (n=30)		
	x	y	φ	x	y	φ
Target position	0.2m	0.0m	0.0°	0.0m	0.0m	360°
Average result	0.1996m	0.0018m	0.008°	0.00003m	0.0006m	359.755°
Standard deviation	0.0006m	0.0005m	0.0036°	0.00019m	0.00024m	1.064°

Tab. 1: Position measurement result

A combination of both patterns of movement is also measurable by this system but is not shown because the uniformity of multiple measurements is not so good without any mechanical restrictions for the robot movement. Therefore they are not comparable.

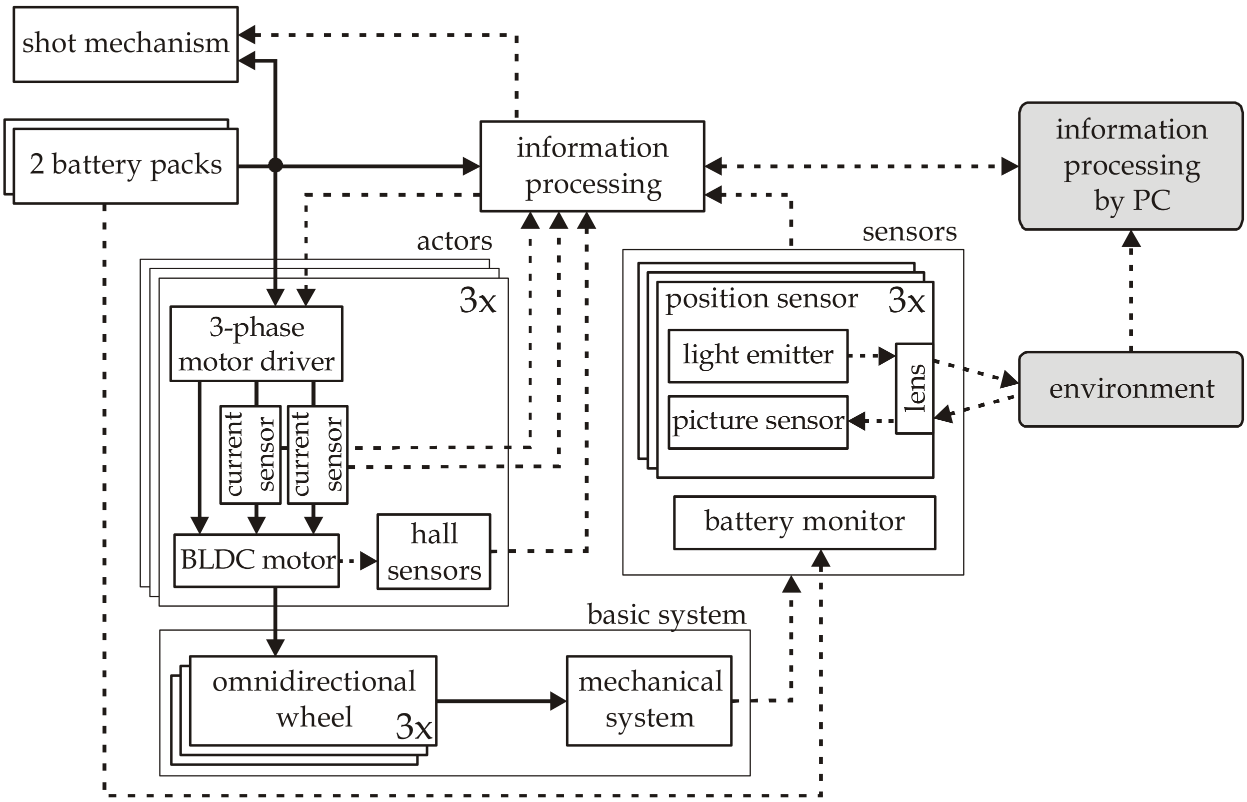


Fig 12: Detailed structure of the mechatronic robot system M11 - measurement system

[15] to exclude unwanted movements in $\vec{E}_y'$ and $\vec{E}_\varphi'$ the robot was coupled to a linear bearing

[16] to exclude unwanted movements in $\vec{E}_x'$ and $\vec{E}_y'$ the robot was coupled to a radial bearing

6. BATTERY MONITORING SYSTEM

Another important information is the battery charging level of the two battery packs including the battery voltage, temperature and mean current consumption. The goal is to increase the longevity, the running time of the robot and to improve the correctness of the reference motor torques calculated by the position controller. The battery monitoring system has to measure seven serial connected LiFePo4 battery cells in each battery pack. To prevent a permanent damage in case of a single cell under voltage a measurement of all battery cells is absolutely necessary. Together with a temperature and current signal the system has to measure nine values per battery pack. To reduce the number of required analog inputs of the information processing system, a multiplexed measuring system is implemented (**Fig 13**). With help of a analog multiplexer[17] a controller is able to select a single cell which is connected to a offset amplifier. This amplifier adapts the measuring range and increases the sensitivity of the measurement system. At least the prepared signal is converted by a 10Bit ADC to a digital cell voltage value. An in the battery pack included NTC[18] resistor as temperature sensor and a current sensor are also part of the battery monitoring system.

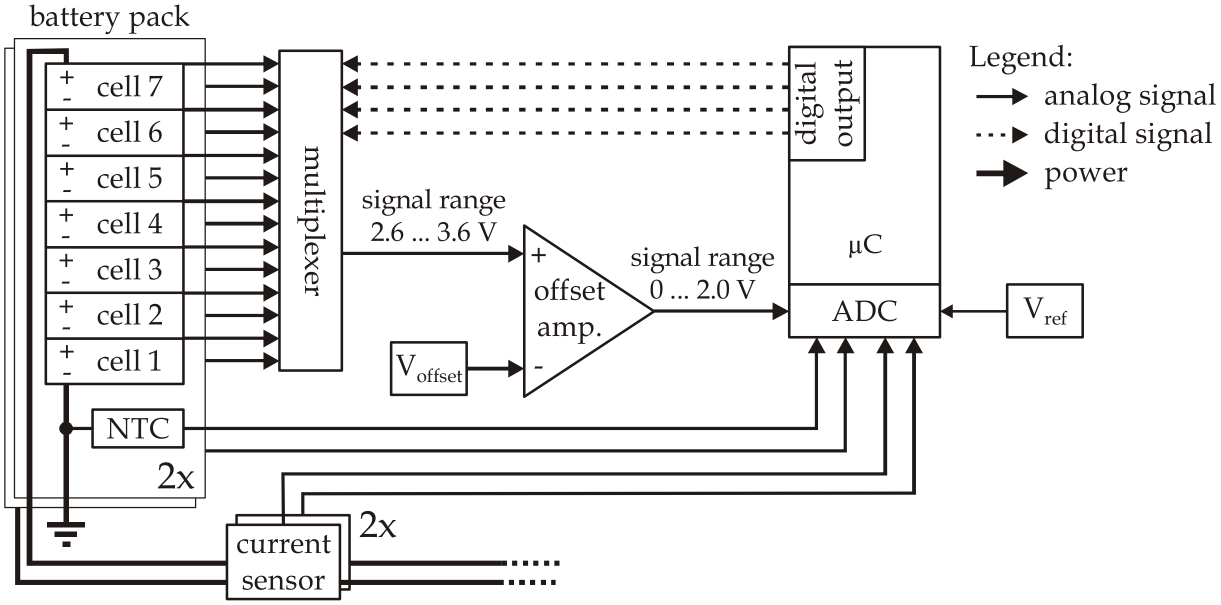


Fig 13: Detailed structure of the battery monitor system with microcontroller (µC) unit

The complete measuring routine is done in less than 2ms and is repeated every 500ms. The following table shows the specifications of the battery measurement system.

	Range	Resolution	max. Error
Cell voltage	2.6 V .. 3.6 V	9 mV	±30 mV
Battery temperature	10 °C .. 90 °C	0.15 °C	±2 °C
Battery current	0 A .. 12 A	10 mA	±250 mA @ 12 A

Tab. 2: Specifications of the battery monitor system

[17] To decrease the influence of the analog multiplexer on the measurement, the analog part of the multiplexer is build with discrete MOSFETs to reduce the resistance of the multiplexer less than 1Ω

[18] NTC: special type of resistor whose resistance varies significantly with temperature

7. INFORMATION PROCESSING

At least a information processing by a CPU is needed to calculate all the controller algorithms, the mechatronic model and the measuring results. This CPU also needs special hardware modules to communicate with the external host PC system and the optical laser sensors, reading multiple analog and digital sensor information and generating PWM signals for actuating the motors. For all these tasks microcontrollers are predestined.

To decrease the degree of software complexity and the error susceptibility the information processing system is split in two subsystems (**Fig 14**), one for hardware near tasks like analog measuring and motor controlling, and the other one for position measuring, position controlling and communication. Each subsystem has its own microcontroller[19] as processing unit.

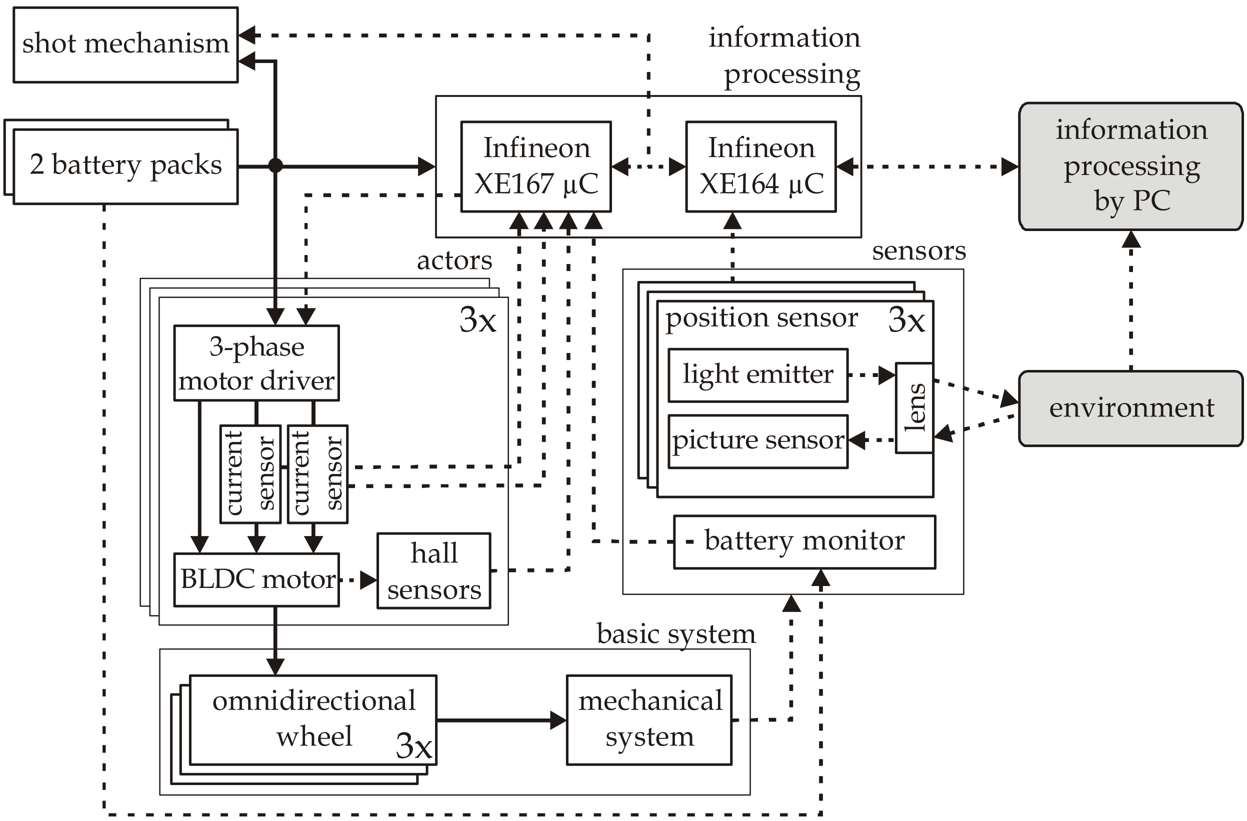


Fig 14: Detailed structure of the mechatronic robot system M11 - information processing

The splitted layout also reduces interaction and timing errors between the controlling tasks of the motor current controllers and the slower working position control algorithm[20] which are running in timer interrupt routines. The two systems are coupled with a digital communication bus based on SPI[21] for data exchange[22] between both controllers with data rates up to 15MBit/s.

---

[19] Both microcontrollers based on the same CPU architecture (C166SV2 16Bit @ 66MHz) and differs only in the integrated hardware periphery modules

[20] Current controller timebase is 50us. Position controller timebase is 5ms

[21] SPI: Serial Peripheral Interface, standardized clocked master-slave bus system.

[22] Exchanged data is normally the three requested motor torques $\vec{T}_{Mr}$, the motor and the battery state. While robot start up multiple other data structures like calibration data is transferred once.

8. **CONCLUSION AND OUTLOOK**

The paper shows that it is possible to implement the required hard- and software structures for all the basic tasks of mobile robotics in a small construction space.

The position control cycle works under conditions for which the system was calibrated well but in reality of mobile robots move over changing floor materials, what is a real problem for the optical position sensor system and also for the drive system. The main problem for the position sensor system is a change of the scaling factor $c = \text{sensor ticks} / 1\text{m}$, wherefore the measured distances are incorrect. For the drive system a change of the wheel friction has the biggest influence. In the future development an adaptive floor material detection and for more autonomy of the robot system an integrated obstacle detecting sensor system is imaginable.

REFERENCES

[DIL11] R. Dill, "Entwicklung eines optischen Messsystems zur Positionsbestimmung von RoboCup-Spielern", 2011

[FUS11] S. Frank, C. Ußfeller, F. Schale, "Odometry for mobile robots with laser sensors", 2011

[GJ07] Gruber, Jockel, "Formelsammlung für das Vermessungswesen", Teubner Verlag, 2007

[RBC01] RoboCup.org, [Internet], [cited 2014 July 22], Available from: http://wiki.robocup.org/wiki/Small_Size_League

[RBC02] The RoboCup Federation, "About RoboCup", [Internet], [cited 2014 July 22], Available from: http://www.robocup.org/about-robocup/

[SCH10] F. Schale, "Implementation von Kommutierungsund Regelungsalgorithmen für elektronisch kommutierte Gleichstrommotoren auf Mikrocontrollern", 2010

[SCH12] C. Schäperklaus, "Entwicklung und Inbetriebnahme eines optischen Messsystems mit CAN-Schnittstelle", 2012

[SSL01] Small Size robot League, [Internet], [cited 2014 July 22], Available from: http://sslrobocup.com/

[SSL02] The RoboCup Federation, "Laws of the RoboCup Small Size League 2014", [Internet], [cited 2014 July 22], Available from: http://robocupssl.cpe.ku.ac.th/_media/rules:ssl-rules-2014.pdf

[USS13] C. Ußfeller, "Beiträge zur Lokalisation und zur modellbasierten Lageregelung mobiler Roboter", 2013

[VDI2206] VEREIN DEUTSCHER INGENIEURE, "VDI2206 - Design methodology for mechatronic systems", June 2004

[WIK01] Brushless DC electric motor, [Internet], [cited 2014 July 23], Available from: http://en.wikipedia.org/wiki/Brushless_DC

CONTACTS

Author:

Florian Schale, M.Sc.
Technische Universität Ilmenau
PF 100565
98693 Ilmenau, Germany
Telefon: +49 (0) 3677 69 1884
Fax: +49 (0) 3677 69 1823
E-mail: florian.schale@tu-ilmenau.de

Coauthors:

Dr. Ing. Marion Braunschweig
Dr. Ing. Sebastian Frank
Technische Universität Ilmenau
PF 100565
98693 Ilmenau, Germany
E-mail: marion.braunschweig@tu-ilmenau.de
E-mail: sebastian.frank@tu-ilmenau.de